InLCA: Selected Papers

The Requirement for Congruence in Normalization

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Abstract. Two purposes for normalization in LCA are presented: resolving non-commensurate units, and assessing significance. Two families of approach for normalization in LCA are described: internal and external. The need for congruence between the normalization and valuation is illustrated by showing the nonsensical conclusions which can result from an approach that is common in North American LCA applications: internal normalization with external valuation. In order to achieve congruence with internal normalization methods, valuation in such instances must be case-specific. External normalization methods bring an added benefit not provided by internal normalization methods: an assessment of relative significance.

Keywords: InLCA; LCA; Life Cycle Assessment (LCA); multi-attribute decision analysis; normalization; valuation

1 Introduction: Definitions and Purposes of Normalization

The step of normalization has been defined in a variety of ways both within and outside of the field of Life Cycle Assessment (LCA). Also, different authors have described the *purpose* of normalization differently. Before considering varied approaches to normalization, we review the variety of stated purposes for normalization, first in the literature of multi-attribute decision analysis, and then in Life Cycle Assessment.

1.1 Normalization in multi attribute decision analysis

Multi-attribute decision analysis (MADA) problems are characterized by a set of *alternatives,* which differ in terms of their performance relative to a set of *attributes.* An oft-cited MADA example is that of selecting an automobile, where three attributes might purchase price (in dollars), fuel efficiency (measured in miles per gallon), and reliability (as rated by a consumer magazine). The attribute values are expressed in different units – they are *non-commensurate.* The purpose of normalization in MADA is to resolve this issue of different units, as stated in a comprehensive review of MADA methods (Hwang and Yoon 1981). "Normalization aims at obtaining comparable scales. [It's purpose is to address] the computational problems inherent to the presence of the different units."

The normalized attribute values will be either unitless or converted to common units. Two simple and popular approaches (among several others that we will review in the next section) are division by the column sum, or division by the column's maximum value.

1.2 Normalization in LCA

We find two different types of approach to normalization in the LCA literature, based on different views about the purpose of normalization.

The first family of approaches addresses primarily the problem of non-commensurate units. In this view, as in the MADA text of Hwang and Yoon, normalization is primarily (or exclusively) seen as an operational prerequisite to valuation, which is the weighting of the impact categories or the impact category results.

For example, the SETAC LCA 'Code of Practice' (Consoli et al. 1993) states the purpose of normalization as one of increasing the comparability of the data from the different impact categories, in order to provide a basis for the valuation step (cited in Seppälä 1999, p 29). Most recently, the National Institute of Standards and Technology (NIST) of the US Department of Commerce has developed a software tool called 'BEES' for LCA-based identification of environmentally preferable products. The BEES user's manual states the purpose of normalization as that of "placing all impact categories on the same scale" (Lippiatt 1998, p 20; 2000, p 28).

In contrast to this first view of normalization, the European LCA literature and the most recent International LCA guidance have consistently seen the purpose of normalization as one of *putting the characterization results in context.* In this view, normalization is seen as a method for "analysis of significance" (e.g., Finnveden and Lindfors 1997, Barnthouse et al. 1997). Three examples are provided below.

ISO Standard 14042.33: "The aim of the normalization of impacts is to better understand the relative proportion or magnitude for each impact category of a product system under study."

Lindeijer 1996 (p 76): "The main aim of normalization is ... to relate the environmental burden of a product (or service) to the burden in its surroundings. In a sense normalization relates the micro world of an LCA to the macro world in which the product/service is embedded."

Guinee 1995 (p 54): "The [characterization results] denote the contributions to well-known environmental problems. The meaning of the resulting numbers, however, is far from obvious. The effect scores become more meaningful by converting them to a relative contribution to the different problem types by means of a normalization."

In summary, this second view of normalization's purpose emphasizes assessing the relative significance of the results

across the different impact categories. The goal of this approach is putting a set of case-specific LCA results into their wider context. Mathematically this is done by dividing the results in each impact category by an estimate of the total impacts in that category for a chosen 'reference system' over a chosen time period. As with all approaches to normalization, this approach also has the effect of adjusting the characterization results to a common unit.

2 Internal and External Approaches to Normalization

In the first section we identified two points of view on the purpose of normalization. In this section we review two corresponding classes of method for normalization. The operational view (normalization as a way to resolve non-commensurate units prior to valuation) is generally linked to a class of normalization methods which we term 'internal' or 'case-specific'. The contextual view (normalization as a way to assess the relative significance of results in different impact categories) is linked to a class of methods which we term 'external' or 'generic' (Table 1).

Table 1: Viewpoints and methods for normalization

Purpose of Normalization	Class of Methods	General description of methods
Normalization is needed to resolve non-commensurate units prior to valuation	Internal or Case-specific	Division of scores in each category by some function of the case s values in that category e.g., maximum value, sum, values for selected alternative, etc.
Normalization helps assess the relative significance of results across categories, puts them in context.	External or Generic	Division of scores in each category by an estimate of the total impacts in that category for a chosen system or region over a chosen time period

2.1 Internal normalization approaches in LCA

One popular method for 'internal' or case-specific normalization in LCA is division-by-maximum. In this approach, the Life Cycle Impact Assessment (LCIA) characterization results for each alternative are divided by the maximum value (across alternatives) for that category; this procedure is repeated for each impact category. This family of normalization methods is termed 'internal' because it uses data that come directly from within the problem at hand.

Internal normalization has been popular in North American LCA. For example, LCA practitioners at Battelle have frequently employed the division-by-maximum approach to normalization prior to an AHP-based weighted sum approach to valuation (see, for example, US EPA 1996). In the US Department of Commerce's BEES software from the National Institute of Standards and Technology (Lippiatt 2000) normalization is achieved using division by maximum value within each attribute category. BEES combines this method of normalization with an AHP-based additive weighting approach to valuation.

There are a variety of 'internal' normalization methods described and used in the MADA literature, several of which have been applied in LCA. One simple comparative approach used in LCA is 'division by baseline' – where the characterization results for each alternative are divided by the results for a selected baseline alternative. One of the problems with this method is the potential for division-by-zero, for flows that are present in the life cycles of alternatives not including the baseline alternative. Another approach is division-by-sum. Division-by-sum is the standard normalization scheme used in the Analytic Hierarchy Process method for MADA (Saaty 1988). Norris and Marshall (1995) illustrated how division-by-sum can lead to a different preferred alternative than division-by-maximum when both benefit and cost data are present in the decision matrix. However, results from a standard LCIA present only cost (that is, 'disbenefit' or 'burden') data. Smith (1999) has shown that division-by-sum can yield illogical results in cases where most alternative's performance scores are bunched near the top of the range for one attribute and near the bottom of the range on another attribute.

More importantly, when *any* method of internal normalization is used in conjunction with case-independent weights, as in BEES, the results are insensitive to the magnitude of performance data and can be reversed by addition or omission of alternative. We investigate these phenomena further below.

2.2 External Normalization Approaches in LCA

There are also a variety of methods available within the class of 'external' methods for normalization. Recall that external normalization entails division of the characterization results C_i for impact category j by a normalization factor A_j. The external normalization factor is, most generally, an estimate of the total impacts in that category for a 'reference system' – a chosen system or region over a chosen time period. Considerations and consequences in the selection of a reference system are discussed in (Bare and Norris 2000).

Note that the external methods require data from outside the case study, while the internal approaches do not. Databases to support external normalization have not yet become available to LCA practitioners in North America. This unavailability has gone hand in hand with an emphasis on internal normalization methods, probably as both a result and as a reinforcing cause.

3 The Requirement of Congruence in Normalization and Valuation

A rather common approach to normalization and valuation in North American LCIA is to combine internal normalization with generic valuation weights. This is the approach taken by NIST's BEES software for example (Lippiatt 1998, 2000), as well as in LCA applications for the US EPA (US EPA 1996).

On the surface the approach appears reasonable. First, the results of a characterization analysis are normalized using an internal method such as division-by-maximum. Then the normalized results are scaled using a set of category weights that may be the result of careful deliberation by a panel of experts. The overall scores for each alternative are computed as the weighted sum of their normalized scores. The problems with this method are that (1) the results are insensitive to performance magnitudes (significance), leading to the potential for obviously absurd results; and (2) rankings may be reversed by the inclusion or omission of alternatives.

Consider a very simple example problem, specified in Table 2. There are two alternatives, each described by three attributes – that is, three life cycle impact categories: global warming potential, acidification potential, and human toxicity. The scores in each impact category would result from applying characterization analysis to the Life Cycle Inventory results for each alternative. Table 2 shows the results before and after normalization, using the division-by-maximum method. Table 2 also lists the importance weights attributed to each of the impact categories. These weights might be derived through reference to an authoritative relative risk evaluation (as in the BEES software), they may be based on panel elicitation exercise conducted specifically to support LCA applications (e.g., Seppälä 1999, Hofstetter 1999) or they might be the result of an in-company exercise to assess and record corporate environmental priorities.

Table 2: Simple example for weighted sum of internally normalized LCIA results

		Alternative A			Alternative B		
	Weights	Characterization Results	Normalized	Weighted	Characterization Results	Normalized	Weighted
Global Warming	10	10 kg CO_2	0.25	2.5	40 kg CO_2	1	10
Acidification	1	25 kg SO_2	1	1	15 kg SO_2	0.6	0.6
Human Toxics	5	20 g Pb	1	5	10 g Pb	0.5	2.5
		Total Score:		8.5	Total Score:		13.1

The overall score for each alternative is given by the weighted sum of the normalized results. Since the results in each impact category represent environmental burdens, the preferred alternative is the one with the lowest overall score. As Table 2 shows, Alternative A has a lower environmental score and is preferred by a considerable margin; Alternative B's score exceeds that of Alternative A by 54%.

First we illustrate the problem of insensitivity to performance magnitudes or significance. Imagine that the data in Table 2 for a second pair of alternatives is identical except for the units (magnitude) of the emissions of CO_2 and lead. Specifically, let's say that the global warming emissions for the two alternatives are now measured in micrograms (10 and 40 for alternatives A and B, respectively), while the releases of human toxics to the environment (expressed as lead-equivalents) are dramatically large, measured in tons (20 and 10 respectively). The absurd thing about internal normalization with external valuation is that the results and conclusions shown in Table 2 will remain exactly the same for this second case. The explanation: Alternative A still performs better than B (by a factor of 4) on the most important of the three categories (global warming) and this advantage outweighs its factor of 2 deficiency with respect to acidification and human toxics, regardless of the absolute magnitude or significance of the global warming-related emissions versus the toxic or acidification emissions.

The combination of internal normalization with external valuation is sensitive to *relative* differences among alternatives but blind to magnitude changes or significance differences among categories. If the results are blind to information about significance, are unchanged by dramatic shifts in magnitude, and thus can clearly lead to absurd results on simple examples were we are able to 'know better', what meaning or reliability can they have on any problem?

Next we illustrate the problem of rank reversal by introducing a third alternative into the mix. This third alternative performs moderately on Human Toxicity and Acidification (in between Alternative A and B for each), and considerably worse than either A or B on global warming. The results of the new 3-way comparison are shown in Table 3. Although Alternative A was originally preferred to B, and nothing about Alternatives A nor B has changed, the presence of Alternative C causes B to now be preferred to A! The fact that such methods have this rank reversal problem is well-known in the MADA literature, and acknowledged in the most recent BEES user's manual (Lippiatt 2000, p 35). In LCA applications, the problem arises from a lack of congruence between the bases for normalization and valuation.

Table 3: Simple weighted sum example with a third alternative added

		Alternative A			Alternative B			Alternative C		
	Weights	Characterization Results	Normalized	Weighted	Characterization Results	Normalized	Weighted	Characterization Results	Normalized	Weighted
Global Warming	10	10 kg CO_2	0.033	0.33	40 kg CO_2	0.133	1.33	300 kg CO_2	1	10
Acidification	1	25 kg SO_2	1	1	15 kg SO_2	0.6	0.6	20 kg SO_2	0.8	0.8
Human Toxics	5	20 g Pb	1	5	10 g Pb	0.5	2.5	15 g Pb	0.75	3.8
		Total Score:		6.33	Total Score:		4.43	Total Score:		14.6

3.1 Congruence

The absurd results illustrated in the previous section occur because internal normalization and external valuation are not congruent. Congruence requires a common basis for normalization and valuation. In the examples above, very common in North American LCA, the weights reflect the importance of each impact category *in general,* while the normalization results reflect the relative performance of the alternatives *with respect to each other.* Congruence will always be absent when internal or case-specific normalization is used in conjunction with weights that are case-independent. In fact, it will also be a problem – regardless of the normalization method used – when the weights are derived using an elicitation process which is not tied precisely to the basis for normalization. This is a problem to which the Analytica Hierarchy Process (AHP) method of weight development is prone, because its trade-off elicitation process makes no explicit use of performance levels on the alternatives. There are two approaches for achieving congruence of normalization and valuation in LCA:

1. **Internal normalization with case-by-case valuation:** conduct valuation for each case, taking the case-specific performance of alternatives explicitly into account;
2. **External normalization with value weights consistent with the normalization database:** Conduct valuation ahead of time for the damages associated with a particular reference system, and then in each case normalize relative to this reference system.

The first solution requires new values elicitation every time the LCA results and/or set of alternatives are modified. The second solution requires an external LCA database. Such a database is not yet available for the US, but is under development by the US EPA.

Note that congruence is not guaranteed but must be carefully pursued in the second solution as well. Specifically, spatial and temporal scope of the emissions inventory used in normalization must be precisely those emissions which are causally-related to the damages considered during valuation, for each impact category. For example, let's imagine that valuation results reflect in part the assessed relative significance of ozone depletion in the year 2000 versus US smog formation in the same year. Congruence allows that different impact categories be defined using different spatial scales, as long as the scale is identical between normalization and valuation for each individual impact category. Thus congruence requires in this case that the normalization data reflect global emissions of ozone depletors, while reflecting smog precursor emissions that impact the US airshed – roughly US emissions.

The requirement for congruence is more difficult to achieve on the spatial dimension of the reference system for impact categories with long-lived pollutants, cumulative effects and/or long delays between emissions and effects. Thus, temporal congruence for annual smog formation is simply achieved using annual smog emissions as the normalization basis, since the cause-effect delay is measured in hours or days, as is the atmospheric lifetime of smog precursors. However, ozone depletion occurring in the year 2000 results from emissions which have accumulated over the past century, some of which have atmospheric lifetimes on the order of centuries.

In summary, the requirements for congruence between normalization and valuation within each impact category appear to warrant more careful attention than they have received to date, in both internal as well as external normalization applications.

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